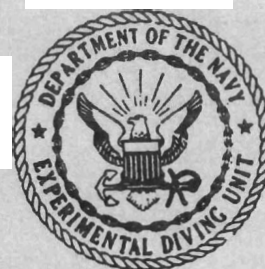




ORIGINAL



RESEARCH REPORT 5-56

NITROGEN-OXYGEN MIXTURE PHYSIOLOGY
Phase 5

PROJECT NS185-005 SUBTASK 5 TEST 4

Added Respiratory Dead Space
(value in personnel selection tests)
(Physiological effects under diving conditions)

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WASHINGTON 25, D.C.

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ABSTRACT

In Phase 2 of this project, it was noted that certain divers tended to develop high carbon dioxide levels during work while breathing nitrogen-oxygen mixtures at depth. This tendency is believed related to respiratory sensitivity to carbon dioxide. The latter might thus form the basis of practical personnel selection tests. The use of added respiratory dead space was considered a possible method of testing sensitivity, perhaps with the advantage of accentuating individual differences. The physiological effects of dead space in diving are also of concern in their own right. The present study was undertaken to assess the possible value of tests involving dead space under various conditions and to obtain more information about the physiological effects of dead space in diving.

End-tidal carbon dioxide tension and other respiratory variables were measured in six subjects at the surface and at 99 feet in the dry recompression chamber during rest and work, with and without one liter of added respiratory dead space. Mean values showed an elevation of carbon dioxide tensions with addition of dead space, and large increases were noted in some subjects especially at depth. However, numerous individual comparisons indicated the reverse. Carbon dioxide levels were generally higher at depth than at the surface, but few approached the values recorded during nitrogen-oxygen exposure in Phase 2. Correlation with the subjects' relative levels of pCO_2 in Phase 2 was noted in certain phases of the study, but the relationships were not entirely consistent.

Factors such as inability to control temperature at depth, certain characteristics of the dead space system, and instability of work rate were considered contributory to the variability and paradoxical nature of some of the results.

Further investigation is required before reaching firm conclusions, and several pitfalls revealed by this study must be avoided.

SUMMARY

PROBLEM

The objective of the investigation was to study the effects of added respiratory dead space under various conditions from the stand-points of (1) possible value in personnel selection tests and (2) general importance in diving.

FINDINGS

The findings were equivocal in many particulars and indicate the need for further investigation along several lines. Regarding selection, the possible role of dead space remains uncertain; but pCO_2 measurements during work and at depth show promise with or without dead space. In several instances, especially at depth, dead space appeared responsible for large increases in pCO_2 . Carbon dioxide levels did not generally approach those noted during nitrogen-oxygen exposure in Phase 2, but several possible reasons for this were evident.

RECOMMENDATIONS

Re-study and extended investigation of carbon dioxide levels in nitrogen-oxygen exposure is recommended, as are further studies related to dead space. Recommendations were also made concerning factors believed responsible for equivocal results in this study.

FOREWARD

Phases 1 and 2 of this study, particularly phase 2, indicated that unusual retention of carbon dioxide by some subjects was probably the cause of apparent loss of oxygen tolerance **during exposure to nitrogen-oxygen mixtures** while working at depth. Both Phase 2 and Phase 3 suggested that the tendency to retain carbon dioxide was related to relative lack of respiratory sensitivity to carbon dioxide and that this characteristic should be demonstrable under a variety of conditions. **It was reasoned** that a measure of sensitivity might provide the basis of a practical personnel selection test directed toward keeping men with this "retention tendency" out of nitrogen-oxygen diving. **The response to added respiratory dead space** appeared to be one of the more promising measures for use in such testing. **The desire to assess it from that standpoint and to learn more about the effects of dead space under diving conditions** led to the present study.

This constituted Phase 5 of NITROGEN-OXYGEN MIXTURE PHYSIOLOGY, Project NS185-005, Subtask 5, Test 4. The work was also expected to contribute to Project NS185-005 Subtask 4 Test 19, THE EFFECTS OF ADDED RESPIRATORY DEAD SPACE. The project as a whole was authorized by the Bureau of Ships in conference, 8 November 1954.

The responsible investigator was LT E. H. LANPHIER, (MC), USNR. He was assisted by the hospital corpsmen and other EDU divers, by the officers of the Unit, and by the summer medical student trainee-assistants.

The initial preparations for the study commenced about 1 August 1955 and included trial runs with subsequent revision of the equipment. Runs for data purposes commenced on 18 August and concluded on 15 September. Computation and preliminary analysis of data continued until about 1 October. Final analysis and writing of the report commenced about 1 October and was interrupted from 15 October to 10 December. The manuscript was completed on 15 January 1956.

This is the final report on Phase 5. Phase 4 was partially progressed and reported in conjunction with Phase 3. The remainder of Phase 4 will be outlined and commenced as soon as possible, as will subsequent phases.

This report also terminates Project NS185-005 Subtask 4 Test 19, THE EFFECTS OF ADDED RESPIRATORY DEAD SPACE. Studies related to dead space will be continued in future phases of Project NS185-005, Subtask 5, Test 4.

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1. OBJECT

1.1 Objectives

- (1) To determine whether physiological tests involving added respiratory dead space have potential value as a means of personnel selection for nitrogen-oxygen diving.
- (2) To obtain further information concerning the physiological effects of added dead space under various conditions.

1.2 Scope

This phase constituted a very limited study. However, it was expected to provide a "yes" or "no" answer to the question represented by the first objective. It was also expected to contribute to the progress of Project NS185-005 Subtask 4 Test 19 as indicated by the second objective.

2. DESCRIPTION

2.1 Effects of dead space

2.1.1 Added respiratory dead space reduces the net alveolar ventilation provided by a given respiratory minute volume (RMV). The effective volume of the dead space is, in effect, subtracted from the actual volume of each breath. Unless alveolar ventilation is in excess of need at the outset, or unless a fully compensatory increase in RMV occurs, addition of dead space will cause a deficiency in alveolar ventilation.

2.1.2 The potential consequences of such a deficiency include inadequacy of the amount of oxygen reaching the blood (anoxia) and failure to remove enough carbon dioxide. In diving, where the partial pressure of oxygen is almost always high, anoxia is seldom likely to result from added dead space. Retention of carbon dioxide is the major problem.

2.2 Dead Space and Carbon Dioxide Sensitivity

2.2.1 Retention of carbon dioxide because of added dead space will cause an increase in the body's carbon dioxide tensions. This, in turn, will normally stimulate respiration. An increase in breathing, especially in the depth of breathing, will tend to compensate for the added dead space. The compensation is not likely to be perfect since a persistent increase in breathing presumably requires a continued stimulus - in this case, elevated carbon dioxide tension.

2.2.2 The extent of compensation for added dead space under diving conditions appears to depend on two main factors:

- (1) the sensitivity of the respiratory control system to an increase in carbon dioxide tension, and
- (2) whether the increase in breathing consists mainly of an increase in tidal volume (depth) or of rate - the latter being considerably less efficient in compensation.

If the second factor is taken into account, the increase in breathing which follows the addition of dead space - or the individual's ability to keep his carbon dioxide tensions within normal limits - should provide an index of respiratory sensitivity to carbon dioxide.

2.3 Significance of carbon dioxide sensitivity

2.3.1 The results of Phase 2 of this study (see Formal Report 7-55) suggested that low respiratory sensitivity to carbon dioxide was a fundamental factor in the development of abnormal carbon dioxide tensions during working exposure to nitrogen-oxygen mixtures at depth. The individuals who showed the most abnormal levels under those conditions generally had above-average carbon dioxide tensions under other conditions including breathing air at rest close to the surface. However, a useful personnel selection test based on carbon dioxide tensions would have to provide means of accentuating the differences between individuals.

2.3.2 Work conducted in conjunction with Phase 3 of this study included carbon dioxide sensitivity tests performed at rest in a limited number of individuals. The method employed was the one which is standard in the Laboratory of Pharmacology at the University of Pennsylvania, where the study was conducted. This involves administration of known percentages of carbon dioxide in the inspired gas with measurement of RMV and end-expiratory carbon dioxide levels.

2.3.3 The results (see Research Report 2-56) showed a reasonable degree of correlation with carbon dioxide levels measured during nitrogen-oxygen exposure at depth in the same individuals. The individuals showing the highest and lowest values in nitrogen-oxygen exposure were also distinctive in their carbon dioxide sensitivity, and this suggests that a sensitivity test as such might well have value at least in predicting extremes of response. However, it seemed probable that predictions short of the extremes would require still further accentuation of individual differences.

2.4 Potential advantages of a "Dead Space Test"

2.4.1 Should a carbon dioxide sensitivity test based on added dead space prove satisfactory, it would have the advantage of requiring no preparation or analysis of special carbon dioxide mixtures. A "response-curve" with as many points as desired could be obtained simply by varying the size of the dead space, and the practicability of a selection test would be considerably enhanced.

2.4.2 An even more important advantage might arise from a fundamental difference between added dead space and inspired carbon dioxide: a man with extreme sensitivity to carbon dioxide can keep his carbon dioxide tension close to normal levels even with a rather large added dead space. With inspired carbon dioxide, no increase in breathing, however marked, can lower the tension below that of the inspired mixture. At the other extreme, dead space in the absence of compensation should be capable of producing carbon dioxide tensions of the same order as the highest inspired mixtures which are likely to be used. By virtue of the possibility of near-complete compensation, a dead space test ought to provide a wider spread of values, and this should make individual differences more clear-cut.

2.5 Importance of dead space

2.5.1 In addition to possible value in connection with personnel selection, the effects of added respiratory dead space have considerable importance in their own right. It is logical to assume that any circumstance which decreased carbon dioxide sensitivity or raised the threshold for respiratory stimulation by carbon dioxide would impair a man's ability to compensate for dead space. Addition of dead space under such conditions could thus be expected to aggravate any tendency toward abnormally high carbon dioxide tensions.

2.5.2 In the nitrogen-oxygen "table-testing" exposures which led to unexpected toxicity, the breathing system included a full-face mask with approximately 500 cc of potential dead space. Preliminary studies in 1954 indicated that 500 cc of added dead space could be expected to cause some increase in carbon dioxide levels even under presumably favorable conditions.

2.5.3 The possibility that dead space contributed seriously to the incidence of untoward reactions in nitrogen-oxygen exposure has been considered repeatedly but has not yet been the object of appropriate study.

2.6 Statement of problem

2.6.1 Reaching the two stated objectives required determining how much the ability to compensate for added dead space differs between individuals, whether the difference is distinct enough to form the basis of a selection test, and if so, whether poor dead-space compensation correlates well with an individual's tendency to show high carbon dioxide levels during working exposure to nitrogen-oxygen mixtures at depth. The type of conditions (rest or work, depth, breathing mixture, and other factors) which show differences most distinctly required study not only because of the need for selection tests but also because of the independent importance of dead-space effects.

2.6.2 The amount of time and manpower which could be expended on a frankly exploratory study was necessarily limited. Consequently, as much information as possible had to be derived from each run, and the procedures were kept as simple as possible.

2.7 Approach

2.7.1 Sufficient information concerning the critical variables was anticipated from appropriate measurements in four sets of runs involving combinations of the following factors, arranged to permit one condition to serve as "control" for the other.

- (1) Rest - work
- (2) Surface - depth
- (3) Added dead space - minimal dead space

2.7.2 The combinations were arranged to minimize the confusion caused by day-to-day variation, which is a serious problem where each subject makes only one run of a given type.

2.7.3 Only six subjects were employed at this stage. They included one example of each extreme of carbon dioxide level noted during nitrogen-oxygen work-exposure in Phase 2. The remainder represented the "mean to high" group in which differentiation is most vital. With one exception, the subjects were also the same men employed in Phase 3.

2.7.4 The most important measurement made was end-expiratory carbon dioxide tension. According to the results of Phase 3, this provides a satisfactory reflection of arterial carbon dioxide tension, which is of primary interest. Respiratory minute volume and rate were of next importance. Breathing resistance, oxygen consumption, and mixed expired gas carbon dioxide percentage were also measured - the latter two only under certain conditions.

3. PROCEDURE

3.1 Location

All runs were conducted in a dry recompression chamber equipped with the necessary instrument cables and sampling connections.

3.2 Respiratory circuit

(A diagram of the respiratory circuit and accessory arrangements is presented in Figure 2.)

3.2.1 A bank of four Scott industrial demand valves, connected in parallel, supplied air to the circuit on inspiration. Of these, 3 were supplied with compressed air at about 125 psi over bottom pressure. The fourth operated at 15 psi over bottom and controlled the end-tidal sampler (see 3.3.3).

3.2.2 The special mouthpiece-check valve assembly was designed to have as low breathing resistance and as low an inherent dead space as possible with the special arrangements required. Expired gas passed through a check valve into the small chamber from which end-tidal gas was sampled and from there into a thin-rubber "dead space bag". The latter had a volume of approximately one liter. This bag had two outlets: one equipped with a check valve and leading to the gas meter, the other leading back to the inspiratory chamber of the mouthpiece assembly. The inspiratory connection was also equipped with a check-valve (inside the inspiratory chamber). A segment of corrugated tubing and a clamp permitted the inspiratory connection of the dead space bag to be closed off.

3.2.3 Expired gas first filled the dead space bag, then passed through the distal exhaust check valve into the gas meter. With the inspiratory connection open, the following inspiration first emptied the dead space bag, then activated the demand valves. The subject thus, in effect, inspired a liter of expired gas before receiving fresh air. With the connection closed, inspiratory gas came entirely from the demand valves. In this case, there was no rebreathing of previously expired gas except for the small amount which could diffuse into the inspiratory chamber during exhalation and that present in the 2-way portion near the mouthpiece.

3.3 Measurements and instruments

3.3.1 Net respiratory minute volume (expired) was measured by means of a dry-test gas meter of adequate capacity. The meter was equipped with electrical contacts which were connected to the event-markers on a Brush oscillograph outside the chamber. One contact registered each liter of gas going through the meter; the other registered every ten liters to provide a check and to assist counting. (Note that this system measured only the net expired gas volume. It did not register the volume of gas which the subject breathed back and forth in the dead space part of the circuit when the dead space inspiratory connection was open. This extra volume amounted to one additional liter per breath. To determine the subject's true RMV for dead space runs, it is thus necessary to add a number of liters equal to the respiratory rate to the net RMV as recorded.

3.3.2 Respiratory rate and breathing resistance were recorded by means of a Statham 1 psi strain gage pressure transducer connected to the inspiratory chamber of the mouthpiece-valve assembly. The gage was connected electrically to a Brush universal amplifier and oscillograph outside the chamber. This provided a record of inspiratory and expiratory pressures which indicated the respiratory rate as well as "breathing resistance".

3.3.3 End-tidal carbon dioxide tension measurement involved use of the Funderburk-EDU end-tidal gas sampling system. This pumped approximately 10 cc of gas from the expiratory sampling chamber of the mouthpiece assembly when the demand valves were activated by each inspiration. This gas was then pumped through the sample-decompressor to the outside where it was run through a Model 16 Liston-Becker Carbon Dioxide Analyzer. The analyzer output was recorded on an Esterline-Angus recording galvanometer. Calibration of the analyzer was in terms of percent carbon dioxide at one atmosphere. Calculation in terms of the ambient pressure to which the subject was exposed yielded the carbon dioxide tension. Calibration of the analyzer was checked with oxygen and 3 known carbon dioxide mixtures at the beginning of each run and with oxygen and the highest mixture during and following the run.

3.3.4 Mixed expired gas measurements considered:

- (1) Determination of carbon dioxide output and oxygen consumption require sampling of expired gas in which the "dead-space" and "alveolar" portions are well-mixed.

- (2) The end-tidal sampler was equipped with an additional sampling pump which drew samples of well-mixed expired gas from the outlet side of the gas meter. These samples were delivered to the outside separately from the end-tidal gas.

- (3) To permit analyzing both samples sequentially with the same carbon dioxide analyzer, the outlet lines of both were equipped with overflow-relief accumulators and attached to a switch-over device which alternately connected each to the Liston-Becker for a 30-second period. The accumulator for the mixed-expired gas samples fed its overflow to a Beckman oxygen analyzer.

(4) In practice, it was found that the volume of gas provided by the sampling arrangements was not always sufficient to assure complete washout of the analyzer sample-cell within 30 seconds. (The Model 16 pickup which had to be employed for the study is equipped with a low-resistance cell - for direct respiratory use - and this involves exceptionally large wash-out space.) Since time did not permit extensive revisions in the system, the attempt to analyze mixed expired gas for carbon dioxide was ultimately abandoned in favor of end-tidal measurement alone. A more direct connection to the oxygen analyzer was then made with the mixed-expired sample-line to permit oxygen-analysis to be continuous.

3.3.5 Oxygen consumption measurements considered:

(1) To provide an approximation of the subject's oxygen consumption, the mixed expired gas measurements with the Beckman oxygen analyzer utilized. This was done only during surface runs since analysis cannot be precise enough to yield meaningful data from depth runs where the oxygen-extraction is very small.

(2) A modification of the nomographic method of Margaria, et al (J. Appl. Physiol. 6:776, 1954) was utilized. This is based on simultaneous measurement of inspiratory RMV and of the oxygen tension of mixed expired gas after absorption of carbon dioxide. (Carbon dioxide was removed by passing the samples through a potassium hydroxide solution before they entered the analyzer.) In this study, the inspiratory RMV was not measured and the expiratory RMV had to be substituted. This entails an error proportional to the deviation of the subject's Respiratory Quotient from one. (During the earlier surface runs, the results of the procedure discussed above were checked by simultaneous determinations by the more laborious "standard" technique. The latter entails collection, sampling and measurement of the entire expired gas volume for the period of measurement with subsequent chemical analysis for oxygen and carbon dioxide. Results of this comparison indicated that the simpler method yielded values consistently higher but rarely more than 0.1 liter per minute in error.)

(3) Oxygen consumption was measured during the last 5 minutes of the main exercise period in most of the "surface" runs.

3.4 Work

3.4.1 Exertion involving a mean oxygen consumption of about 1.4 liters per minute was intended for the work-phases of the runs. (This is the work-rate associated with "long-pull" swimming, used in most recent EDU studies.)

3.4.2 The subjects exercised by pedaling the hydraulic bicycle ergometer. Preliminary "calibration" of the ergometer indicated that the desired average oxygen consumption of 1.4 liters per minute was achieved with 15 psi pump circuit pressure at a 60/min. pedaling rate. (See Appendix 8.2)

3.5 Temperature

3.5.1 Since the runs were conducted during hot weather and in the re-compression chamber, uncomfortable warmth on the part of the subjects was anticipated. Steps were taken to keep the men as comfortable as possible.

3.5.2 During surface runs, a large electric fan and a blower were directed on the subjects, and they were generally fairly comfortable.

3.5.3 At depth, only the fan could be used to supplement frequent compressed-air ventilation of the chamber. Unfortunately, chamber temperature was recorded poorly, no measurements of humidity were made, and subjects' body temperature was not measured. (See Appendix 8.3)

3.6 Subjects

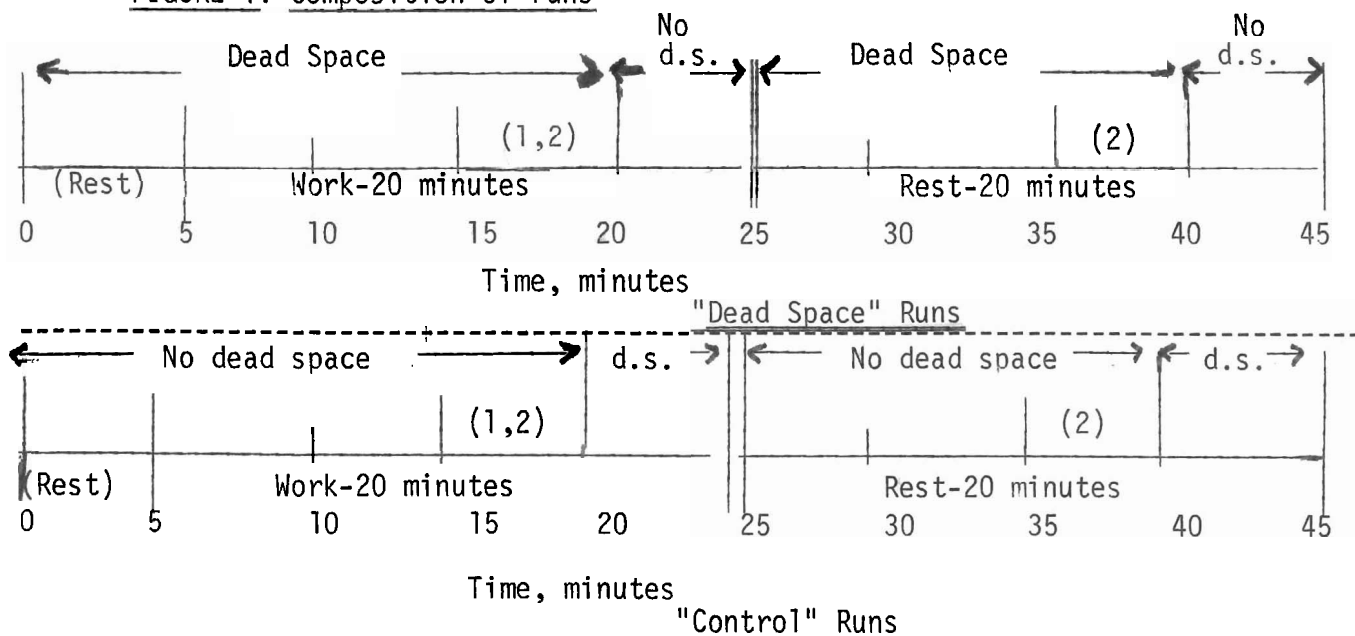
3.6.1 Six subjects were employed in this study. With one exception (LCDR DWYER was substituted for BN1 CIRELLI, who had been detached), the group was the same as that studied in the evaluation of the end-tidal sampling system and other factors. (Research Report 2-56). All had been subjects for the Nitrogen-Oxygen Physiology wet-tank runs (Formal Report 7-55).

3.6.2 DWYER had shown the highest end-tidal $p\text{CO}_2$ in the nitrogen-oxygen study, while LANPHIER's values were among the lowest. The other subjects were drawn from the "average or above" group of that study.

3.7 Runs

3.7.1 Runs were of two basic types, indicated in Figure 1, below.

FIGURE 1: Composition of runs



NOTE: (1) Oxygen consumption measured during surface runs.
(2) Mixed expired gas % CO_2 recorded and carbon dioxide output computed during some runs.

Each subject made one run of each type at the surface and at a pressure equivalent to 99 feet of depth. Air was the breathing medium throughout.

3.7.2 Each run consisted of a 5 minute settling down period followed by 20 minutes of work and 20 minutes of rest. In the "dead space" runs, the 1000 cc dead-space bag was in the circuit except during the last 5 minutes of work and of rest. In the "no dead space" runs, the procedure was reversed (See Appendix, 8.4).

3.7.3 Each subject made 4 runs "for the record". Several repeats had to be made because of various errors and failures. Definite criteria for repeating were established to avoid prejudicing the results.

3.7.4 The order in which each subject made the various runs was randomized as much as possible.

3.8 Handling of data

3.8.1 Respiratory minute volume, breathing resistance, respiratory rate, and end-tidal carbon dioxide analyzer deflection were recorded automatically throughout all runs. Following the runs, data sheets were prepared from these records. Carbon dioxide tensions were derived from the analyzer deflections by means of appropriate translation tables based on the calibration curves and the ambient pressure.

3.8.2 Values for tabulation were derived by averaging the figures for the last 5 minutes of the principal "dead space" or "no dead space" periods of rest and work and by averaging the last 2 minutes of the "shift" periods.

3.8.3 Oxygen consumption was computed as described above (See 3.3.5).

3.8.4 Other details of the handling and analysis of data are apparent in Section 4., Results.

4. RESULTS

4.1 General

The basic data are presented in Tables 1 and 2. Table 3 indicates the various means and mean differences. Table 4 presents related pCO₂ data from Phases 2 and 3. Table 5 gives oxygen consumption measurements in the present study, and Table 6 is concerned with breathing resistance.

4.2 Personnel selection aspects

4.2.1 Criteria

(1) The criterion for judging the predictive value of a procedure is the degree of correlation between the results of the "test procedure" and the characteristic it is intended to predict. Here, the only available standard is the order or "rank" of the subjects according to pCO₂ values recorded during nitrogen-oxygen exposure in Phase 2 (Table 4).

(2) To show promise from the standpoint of personnel selection, a given phase or type of observation in this study should indicate a reasonable degree of correlation with that order.

4.2.2 Dead space and selection

(1) The most obvious measure to examine for evidence of correlation is simply the pCO₂ recorded with dead space under various conditions. Note that under most of the conditions studied, the addition of dead space made only a small difference in the mean values of pCO₂ and had little if any favorable effect on the correlation of individual values.

(2) Another measure which might show predictive value is the change in pCO₂ associated with addition of dead space. There is indeed a large difference between individuals in respect to this change. Note that in numerous instances the pCO₂ was lower with the dead space than without it - a finding which appears paradoxical (See DISCUSSION, 5.1.0). Some individuals consistently showed increases, as expected, and some of the increases were quite large. However, there is no evidence of correlation between the direction or degree of change and the Phase 2 data. Only DWYER ranks "high" consistently in both respects.

(3) Response to dead space was expected to furnish an unusually good index of carbon dioxide sensitivity, but the frequency of "negative" changes made analysis of the data in these terms a highly questionable procedure.

4.2.3 Carbon dioxide levels and selection

(1) Despite the questionable significance of the dead space results, examination of pCO₂ values recorded in the study as a whole is of some interest. Under none of the conditions of study were the pCO₂ levels as high as during nitrogen-oxygen exposure even though a few subjects approached their previous levels. However, under several of the conditions of study the pCO₂ values "ranked" the subjects in about the same order as did the measurements of Phase 2.

(2) Reasonable correlation is evident in the work runs, taken as a whole, and in the aggregate of measurements at 99 feet. Work at 99 feet, with and without dead space, also indicates an encouraging degree of correlation. While no single condition or set of runs yields perfect results according to this criterion, "work at depth" comes much closer than "rest", or "surface" with or without work. In the study as a whole, the presence of dead space appeared to improve correlation; but it made relatively little difference in specific situations. It should also be noted that presumably similar circumstances did not always yield the same pattern of results.

4.3 Physiological effects of dead space

4.3.1 Carbon dioxide tension

(1) The mean values invariably show higher pCO_2 in the presence of dead space, but the differences are uniformly very small except during work at 99 feet - and that difference is only 5.5 mmHg. The small magnitude of the mean differences is not surprising in view of the fact, already mentioned, that many of the measurements indicated a change in the reverse direction (See DISCUSSION 5.1.1).

(2) Note, however, that the highest pCO_2 values were encountered in the presence of dead space. In addition, some subjects (DWYER, COGGESHALL, LANPHIER) rather consistently showed a rise in pCO_2 with dead space; and some of the increases were large. For example, the highest pCO_2 in the entire study was one of DWYER's: 67 mmHg. (99 feet, "dead space run", work). This was 19 mmHg above the corresponding control value, and a drop of 13 mmHg occurred within 5 minutes when the dead space was shifted out of the circuit.

4.3.2 RMV and rate

(1) The respiratory minute volume figures (Tables 1 and 2) show too much overall variability to be of much interest in themselves. However, the fact that they are net volumes makes them a ready index of the subject's effective compensation for dead space (note, however, that they do not take into account the interaction of the respiratory rate and the subject's own dead space). In all but one comparison, the mean values show a drop in net RMV corresponding to a rise in pCO_2 and vice versa when dead space is added or removed. Examination of individual cases indicates that this relationship does not invariably hold, however, even in the "shift" situations where work-rate should have been quite constant.

(2) Respiratory rates tended to be higher in the presence of dead space, but no detailed analysis of rate-RMV-dead space relationships was considered warranted.

4.4 Effects of depth

(1) During work, the mean $p\text{CO}_2$ values tended to be higher at 99 feet than at the surface. During rest, the reverse was true. In both cases, the differences were small. As a consequence of these opposite trends, the work-rest $p\text{CO}_2$ difference was considerably larger at depth than at the surface. This was particularly true with dead space. In those phases, it was almost as large as in the nitrogen-oxygen runs of Phase 2 (15.5 mmHg), but both resting and working values were considerably lower. While some subjects showed greater surface-depth difference than others, no correlation with Phase 2 "rank" is evident. Note that all of the unusually high $p\text{CO}_2$ values in this study were obtained during work at depth but that individual trends showed considerable variability.

(2) In general, RMV and rate were lower at 99 feet than at the surface during work and higher during rest, i.e. they usually maintained the expected relationship to $p\text{CO}_2$; but some of the individual variations clearly indicate that the subject's work rate was not the same at depth as at the surface and that this modified the apparent relationship. (See also DISCUSSION 5.2.2(3)).

4.5 Miscellaneous observations

4.5.1 Work rate

(1) Oxygen consumption data (surface runs only) is presented in Table 4. It shows considerable variation, and most of the values are above the intended mean of 1.4 liters per minute.

(2) The RMV figures in Tables 1 and 2 ("no dead space" phases) also provide an indication of work rate. The means are considerably above those of the nitrogen-oxygen study (about 27 lpm), and the individual values show great variation even in the same man under similar conditions.

(3) During his "dead space" run at 99 feet, HOLLINGSWORTH ignored the cycling rate-control system. He was obviously overworking and was unable to finish the run. (The run could not be repeated because of subject's imminent departure on leave to be married.) The data from this run was recorded but omitted in averaging. Note that the net RMV was 31.5. Since dead space was in the circuit and the rate was 24 breaths per minute, the subject was actually ventilating about 55.5 lpm.

4.5.2 Breathing resistance

The breathing resistance data was not analyzed in detail, but the formula and "constants" in Table 5 indicate the order of magnitude encountered under the various conditions. The increase with depth was considerable, but the levels did not exceed those generally accepted in scuba.

4.5.3 Temperature

Measurement of chamber temperature was not done consistently, and no measurements of body temperature were made. Subjects were reasonably comfortable during surface runs but felt acutely overheated during the work phases of the 99-foot runs.

4.5.4 Symptoms

In general, the complaints of the subjects were readily attributable to work, heat, and the respiratory apparatus. None appeared to related specifically to carbon dioxide excess or of much significance from other standpoints.

However, DWYER reported bizarre symptoms following his "surface-dead space" run. The run itself was uneventful, and the highest pCO_2 recorded at any time was 56.3 mmHg. During the run, the subject noticed only "the incipient feeling of a headache", and nothing developed. The symptoms experienced following the run can be summarized as follows:

About 80 minutes after the run, DWYER experienced sudden onset of vertigo severe enough that he required assistance in standing. This was accompanied by severe nausea and heavy sweating. The vertigo lasted about 3 minutes, the sweating slightly longer, and the nausea about 20 minutes, gradually diminishing. Subject went to lunch despite nausea and ate fairly well. Headache ("behind the eyes") began during lunch, was quite severe for about 20 minutes, subsided while he rested. Some residual headache remained most of the afternoon. There were no further symptoms.

5. DISCUSSION

5.1 Dead space effects

5.1.1 Paradoxical pCO_2 changes

The most striking feature of the study is the generally indefinite nature of the findings. Much of this vagueness can be traced to one feature of the data: the frequency with which lower pCO_2 levels were measured with added dead space in the circuit than without it. With very few exceptions, such "negative differences" occurred in only half of the subjects (and not invariably in them) but had a profound influence on the mean values. The fact that negative differences occurred this frequently also raises serious questions. If they are artifacts in some sense, which seems most likely, they question the significance of all the observations. If they are by any chance valid, current thinking about dead space must be revised radically. The possibilities should be examined:

5.1.2 Previous observations

The accepted concept about added dead space and its effects was discussed in 2. DESCRIPTION. The few published studies and EDU's prelimi-

nary dead space work (See Appendices, 8.5) generally uphold this concept and offer very little precedent for a drop in $p\text{CO}_2$ with added dead space.

5.1.3 Possible sources of error

(1) Type of dead space

(a) The dead space arrangements (see PROCEDURE, 3.2, and Figure 2), involved a collapsible bag rather than the usual rigid "dead volume". (Note that the arrangement differs from the usual scheme of "gas saver" type scuba which involves the "bag" principle. There, the arrangement attempts to trap only the first part of expiration. In the apparatus of the present study, the dead space bag deliberately trapped the last part of expiration.) This arrangement had at least one feature which might help account for the results. On inspiration with the bag in the circuit, the subject first emptied the bag and then tripped the demand valves to complete his inspiration. Subjects could not be kept unaware of the presence or absence of added dead space, and most of them also realized that they got no fresh gas until the demand opened. However, tidal volumes were almost invariably larger than bag volume even at rest without dead space, so the demand valves would have been actuated even without any compensatory increase in tidal volume.

(b) LANPHIER, being concerned about this situation tried on occasion to see whether he could consciously gage the amount of air he needed to draw from the demand to compensate for the dead space. He concluded that he had nothing but his respiratory drive to guide him and could not possibly judge whether he was actually compensating adequately or not, and his $p\text{CO}_2$ invariably rose when dead space was in the circuit or fell when it was removed.

(c) FUNDERBURK constructed the dead space arrangement and was well-acquainted with its implications. He was not aware of consciously modifying his breathing, but he almost always showed an increase in net ventilation and a considerable drop in $p\text{CO}_2$ when dead space was present. His "negative differences" were the most consistent and generally the largest noted. It can also be recalled from Phase 3 that the same subject approximately doubled his RMV when he discovered that a certain feature of his normal respiratory pattern was causing the Lambertsen sampler to function improperly.

(d) It is impossible to rule out the possibility that this system and awareness of its characteristics may have modified the responses at least of some subjects. Conscious awareness of the necessity for increased breathing may well constitute an additive respiratory stimulus even where no index of the adequacy of ventilation is present. Despite certain disadvantages, the more common "rigid volume" type of dead space apparatus is probably preferable; and obviously, wherever possible, the tests should be "blind" - subjects not knowing whether added dead space is present or not. The importance of "conscious awareness" as a respiratory stimulus could be the subject of an extremely interesting study in itself.

(2) Sampling errors

(a) Another possible explanation of the unexpected results is that the sampling system might have introduced an error when the dead space bag connection was open. A sampling error would occur if gas with lower $p\text{CO}_2$ than true end-tidal gas were in the sampling chamber at the moment when the sampler operates.

(b) With the dead space in circuit, the sampler is triggered later - when the demand valves are tripped after emptying of the bag. This bag might permit lower - CO_2 gas to diffuse back into the sampling chamber - aided, perhaps, by movement of the bag-**gas on inspiration**. It is difficult, however, to see how such a sequence of events could produce enough error to explain the results. **Especially during work, the bag-gas itself should show a considerable increase in $p\text{CO}_2$ with addition of dead space.** The fact that the apparent drop in $p\text{CO}_2$ is frequently accompanied by an increase in net ventilation also argues against sampling error as an explanation. **In any case, the possibility of such sources of error must be minimized in future apparatus.**

5.1.4 Implications

(1) The lack of any adequate precedent and the fact that one or more extraneous factors could explain them argue against the physiological significance of the low $p\text{CO}_2$ values recorded in some subjects in the presence of added dead space. **Assuming that these values are artifact** the next question is whether the same factors were operating to some extent in all subjects - reducing the observed response even when it was positive.

(2) Existence of this uncertainty, regardless of what the answer may be, makes it impossible to conclude anything definite about the possible value of dead space in selection tests. **If it could be** assumed that the questionable results were artifacts of some sort, the overall impression would be encouraging. **The results certainly** do not make this aspect of dead space any less worthy of further investigation.

(3) The paradoxical results also make it difficult to reach conclusions about the general importance of dead space effects in diving. It would, for example, be difficult to prove that the small positive mean differences are significant. When differences in both directions occur fairly frequently, the likelihood that all differences are largely due to random variation increases. **Here,** however, it is probably more than coincidental that 3 of the subjects quite consistently showed positive differences, that several of these were much larger than any of the negative differences, and that all of the unusually high $p\text{CO}_2$ values were recorded in the presence of dead space. **It is also of interest that the** positive differences noted were predominantly larger at depth than at the surface.

(4) Further study, with elimination of all the possible sources of error mentioned, is clearly required. In such a study, two possibilities should be kept in mind and evaluated if possible: (1) that accepted concepts about dead space response may be in error, and (2) that there may be some unsuspected factor, aside from those mentioned, which makes response to a "bag" type dead space differ from the usual.

5.2 Effects of depth

5.2.1 Non-duplication of Phase 2 results

One of the secondary motives behind this study was to determine whether breathing air during exertion at 99 feet would produce increases in end-tidal pCO_2 like those observed using 45% oxygen-55% nitrogen at the same depth in Phase 2. It clearly did not. The mean pCO_2 was slightly higher at depth than at the surface, but neither the means nor most of the individual values during work at 99 feet approached those observed with nitrogen-oxygen.

5.2.2 Possible explanations

Several possible reasons for failure to duplicate these results are worth considering:

(1) The most alarming possibility is that the nitrogen-oxygen results themselves were in error. This possibility was seriously considered at the time of that study and later (Phase 3) and has been deemed unlikely. However, the failure of the present results to confirm the previous ones makes repeating those runs even more desirable than before.

(2) The possibility that errors in sampling or analysis were at fault in the present study cannot entirely be ruled out although the precautions taken should have been ample at least for the "no dead space" phases (See 5.1.3 (2)). The mean pCO_2 values at the surface were also lower during both work and rest than those for the same subjects in the "near surface-air" phase of the nitrogen-oxygen runs (Phase 2) and the Phase 3 study. This might indicate an overall error of some kind.

(3) Difference in conditions

(a) There were very great differences between the circumstances of the Phase 2 runs and these. In Phase 2, the men were swimming horizontally underwater with a full-face mask. Here they were upright riding a bicycle in a dry chamber, using a mouthpiece and noseclip with a different breathing system. As pointed out by some subjects and concurred in by all, the entire "feel" of the situation, not least in regard to breathing, was entirely different. In many cases, the work-rate was different also (5.4.1).

(b) Perhaps the most important difference was in the temperature. Underwater, there was no systematic difference in temperature between surface and depth runs, and the subjects were always reasonably comfortable. In the chamber runs, temperature at the surface was not much of a problem; but at depth, the heat was almost in-

tolerable especially during work. Increased body temperature is known to be a respiratory stimulus, so the temperature difference might have cancelled out a large part of any normal surface-depth pCO_2 difference.

(c) In his "dead space" run at 99 feet, LANPHIER's pCO_2 values were all unusually low even for him. They markedly influenced the means, and even though his pCO_2 was higher in the dead space phases, it did not reach the "no dead space" level of his other depth run. The main subjective difference between the two 99 foot runs was that the heat seemed much worse in the run which showed the low pCO_2 levels.

(4) Finally, there is no actual evidence that air should have the same effect on breathing at depth as will a 55/45 nitrogen-oxygen mixture. The probability that nitrogen was responsible for the noted changes in Phase 2 suggested that air, yielding a higher partial pressure of nitrogen, would produce an even greater change. But it is possible that a certain partial pressure of oxygen has to be present simultaneously, and the situation may involve complex inter-relationships, biphasic effects, or both. Whatever the explanation for the lack of notable surface-depth difference in this study, the relationships involved deserve further investigation.

5.3 Personnel selection

5.3.1 General observations

The possible value of dead space as an adjunct to personnel selection received little illumination from this study, but an opportunity was provided to gain some insight into other possible methods of predicting a man's tendency to retain carbon dioxide under certain conditions.

5.3.2 Carbon dioxide levels, per se

(1) It was noted that the relative level of a subject's end-tidal pCO_2 under some conditions correlated rather well with comparable observations in Phase 2 (See 4.2.3). Work alone seemed to have predictive value in this sense, and work at 99 feet was even more specific. Although its influence was not impressive for obvious reasons, dead space appeared to improve the overall specificity to some degree. The pitfalls of evaluating "correlation" with so few subjects and so few observations must be kept in mind. The comparisons made here are necessarily crude.

(2) If a selection test could be based on pCO_2 levels developed during work at the surface, this might be a practical procedure. Having to use work at depth, even though air could be employed as the breathing medium, offers scarcely any advantage over exposing the subject to exactly the conditions for which the test is supposed to have "predictive value": nitrogen-oxygen exposure during work at depth.

(3) If dead space actually has the expected effects - and not those shown in this study - its use in conjunction with work at the surface should prove of some value as a means of selection.

5.3.5 Reproducibility

In any case, one of the main problems of a selection procedure will be its reproducibility. A test which had to be run several times with a given man to yield significant results would probably be impractical. The lack of consistency apparent in some of the results of this study is not encouraging from that standpoint, but elimination of some of the uncontrolled variables should be helpful.

5.4 Miscellaneous factors

5.4.1 Work rate

(1) The respiratory minute volume (RMV) is modified by various factors, but it varies primarily in accord with the oxygen consumption and carbon dioxide production. Changes in work-rate can thus produce changes in RMV much greater than those associated with such variables as respiratory sensitivity to carbon dioxide. If, as in the present study, the work-rate is highly variable from run to run, comparison of individual RMV values is useless unless oxygen consumption and/or carbon dioxide output can be measured simultaneously.

(2) It was hoped that the hydraulic bicycle ergometer would provide an even more reproducible form of work than stationary swimming. To date, it has failed to do so and leaves the laboratory with no dependable method of exercising subjects except in the water. The bicycle must be improved or supplanted.

5.4.2 Wet vs. dry

(1) This study was conducted in the dry chamber in part because of supposedly greater convenience and in part to explore the desirability and possible problems of working "in the dry". There are certainly many procedures which would be difficult or impossible underwater.

(2) It was interesting to note, however, that a surprising number of problems are more easily handled underwater than in the chamber. Control of temperature is the foremost example. Failure of available measures to keep the subjects comfortable during the depth runs may have made a very significant difference in the results (5.2.2 (3)), and there seems to be no point of doing any potentially "temperature sensitive" study in the dry chamber until air conditioning is installed. Without air conditioning, uncontrolled temperature will be a severe handicap, if not an insurmountable obstacle, in solving any problem which cannot be studied readily underwater.

(3) To date, the importance of differences between swimming and dry-land forms of work is unknown. The effect of position and hydrostatic factors on breathing, for example, might be of great importance in certain problems. Since investigations which require dry conditions can be foreseen, the differences deserve investigation. In the meantime, continuing to conduct studies underwater whenever possible appears to be the best course.

5.4.3 Breathing resistance

Although inspiratory and expiratory pressures were recorded at the mouthpiece unit and found to increase considerably at depth, they were neither objectively or subjectively bad according to current standards except at unusually high RMV's. The concurrent increases in $p\text{CO}_2$ were not considered great enough to warrant any attempt to discern interrelationships between CO_2 levels and resistance. This should also be the subject of a specific study.

6. CONCLUSIONS

6.1 Conclusions

- (1) The frequent observation of lower end-tidal $p\text{CO}_2$ with added respiratory dead space prevents reaching firm conclusions about the main problems of the study.
- (2) Although probably an artifact, these observations indicate that re-consideration of current concepts about dead space is desirable.
- (3) Further investigation of dead space effects is required and should include consideration of basic mechanisms involved in response.

6.1.2 Dead space and personnel selection

In spite of equivocal results, the possible value of dead space response tests in personnel selection remains worthy of further investigation.

6.1.3 Dead space effects, general

- (1) If the "positive" changes observed are valid, added dead space in the order of one liter is capable of producing large increases in $p\text{CO}_2$ at least in some subjects and especially at depth.
- (2) Further study is indicated and should include investigation of the effects of smaller dead space volumes.

6.1.4 Personnel selection, general

- (1) Carbon dioxide levels, with or without dead space, show an encouraging degree of correlation with Phase 2 results under certain conditions.
- (2) According to available information, measurements during work, especially at depth and possibly with added dead space, are the most promising basis for selection tests.

6.1.5 Effects of depth

- (1) Except in a general way, the study did not confirm Phase 2 "work-depth-nitrogen" observations relative to carbon dioxide levels.

(2) There are numerous possible reasons for this lack of confirmation but the original observations should be checked and extended as soon as possible.

6.1.6 Miscellaneous

(1) Further studies involving dead space should assure that the subjects do not know when dead space is added or removed, and a rigid type of dead space volume should be employed primarily.

(2) There is no use of conducting conceivably "temperature sensitive" studies in the dry chamber without air conditioning or some equally effective means of controlling body temperature.

(3) The importance of various differences between "wet" and "dry" conditions needs to be investigated.

(4) The bicycle ergometer is not sufficiently reliable in its present form. A dependable "work machine" is urgently needed.

6.2 Recommendations

6.2.1 Re-investigate carbon dioxide levels in nitrogen-oxygen exposure at earliest possible time. If previous findings are confirmed, extend study to elucidate mechanisms and parameters of effect.

6.2.2 Conduct further studies of dead space effects, avoiding possible sources of error noted in this study, including smaller dead space volumes, and considering fundamental relationships.

6.2.3 Pursue investigation of possible personnel selection procedures, concentrating on measurements during exertion with and without added dead space.

6.2.4 Take steps to air-condition at least one recompression chamber. Until this is done, conduct studies underwater whenever possible.

6.2.5 Intensify efforts to obtain a satisfactory "work machine".

6.2.6 When time permits, obtain information concerning:

(1) The influence of body temperature on oxygen tolerance, respiration, and other related functions.

(2) Importance of various conditions which differ between studies conducted underwater and "in the dry".

7. FIGURES AND TABLES

7.1 Figures

- 7.1 1. Composition of Runs (in text: PROCEDURE, 3.7.1).
2. Apparatus for Dead Space Study.

7.2 Tables

1. Respiratory Measurements, Runs at Surface.
2. Respiratory Measurements, Runs at 99 feet.
3. Mean $p\text{CO}_2$ values and differences.
4. Rank of Subjects According to $p\text{CO}_2$.
5. Oxygen Consumption Data.
6. Breathing Resistance.

FIGURE 2

APPARATUS FOR DEAD SPACE STUDY

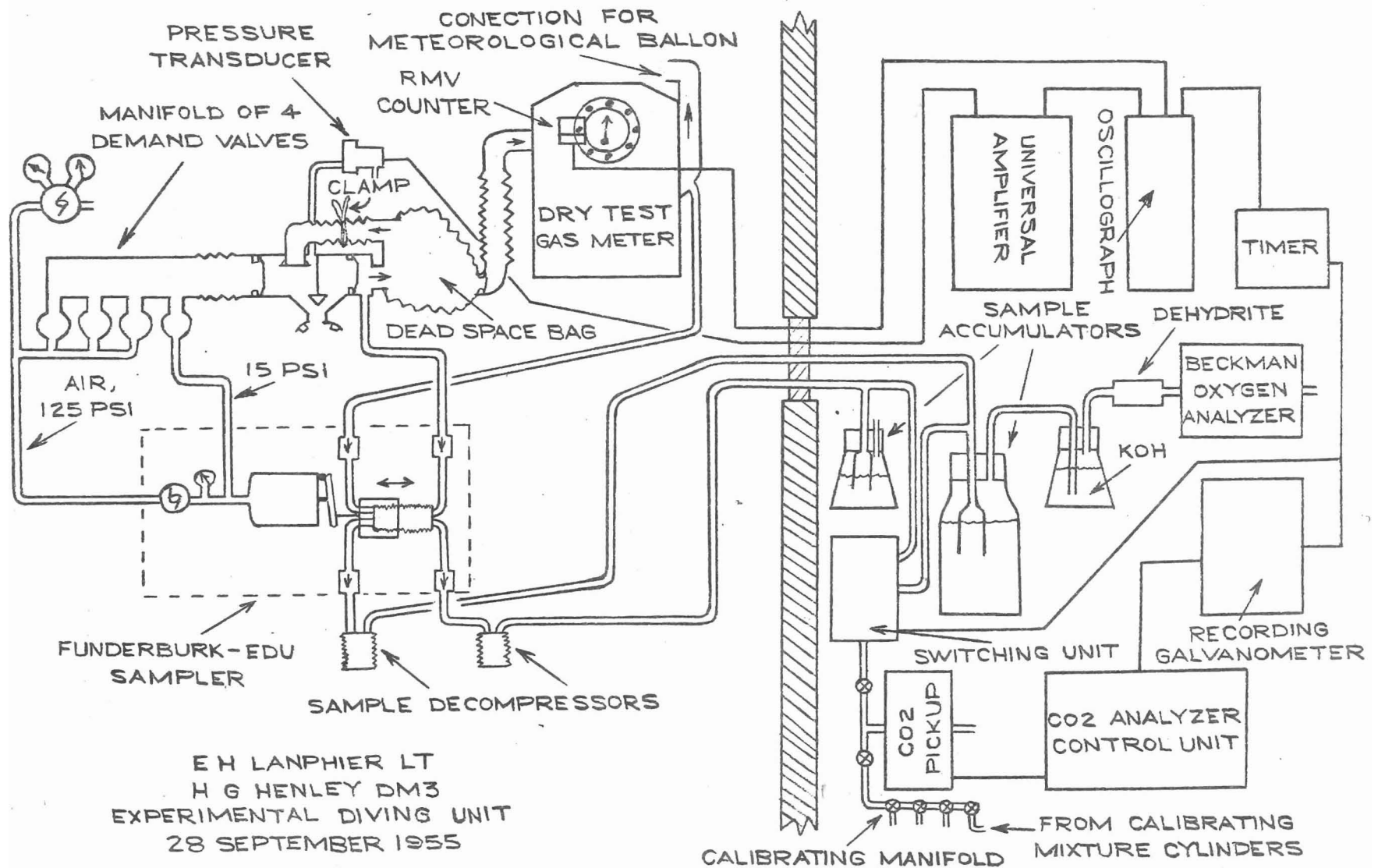


TABLE 1. End-tidal carbon dioxide tension, respiratory minute volume, and respiratory rate.

RUNS AT SURFACE

		WORK (20 minutes)						REST (20 minutes)					
		Main Period (15 min.)			Shift Period (5 min.)			Main Period (15 min.)			Shift Period (5 min.)		
		pCO ₂ mm. Hg	RMV* L/min.	Rate bpm	pCO ₂ mm. Hg	RMV* L/min.	Rate bpm	pCO ₂ mm. Hg	RMV* L/min.	Rate bpm	pCO ₂ mm. Hg	RMV* L/min.	Rate bpm
"NO DEAD SPACE" RIMS	SUBJECT	No added D.S.			1000 cc added D. S.			No added D. S.			1000 cc added D. S.		
	Coggeshall	42	40.4	16.4	44	37.5	20.5	33	9.6	11.6	37	8.0	10.0
	Dwyer	46	50.4	16.8	51	41.0	18.5	39	9.6	7.0	39	6.0	5.5
	Funderburk	52	26.8	7.4	48	30.0	14.0	37	8.6	3.0	37	9.0	4.0
	Hanes	44	36.2	11.8	51	32.0	13.0	35	8.6	4.5	33	6.5	4.5
	Hollingsw.	49	32.8	14.4	52	33.5	18.0	40	10.6	11.4	42	7.5	14.5
	Lanphier	38	45.2	20.0	42	40.0	22.5	35	11.2	10.8	39	7.5	8.5
	MEAN	45.2	38.6	14.5	48.0	35.7	17.8	36.5	9.7	8.1	37.8	7.4	7.8
"DEAD SPACE" RUNS		1000 cc added D. S.			No added D. S.			1000 cc added D. S.			No added D. S.		
	Coggeshall	53	25.6	18.2	49	27.0	15.5	46	6.6	12.2	39	8.5	10.0
	Dwyer	51	31.6	13.2	47	39.0	13.5	38	7.6	5.6	36	8.0	5.0
	Funderburk	51	29.0	12.4	52	30.5	11.0	36	11.6	6.6	37	9.0	2.5
	Hanes	42	28.4	11.0	45	32.5	11.0	29	8.4	5.2	31	8.5	5.0
	Hollingsw.	43	27.4	17.6	44	29.5	13.5	40	8.2	10.2	37	8.0	10.5
	Lanphier	41	36.0	22.4	38	42.5	17.0	36	9.4	9.2	34	9.5	6.5
	MEAN	46.8	29.7	15.8	45.8	33.5	13.6	37.5	8.6	8.2	35.7	8.6	6.6

*NOTE: RMV represents net volume of gas expired through meter. To obtain subject's total expired volume, when breathing with dead space bag in circuit, add one liter per breath. (Values given are at ambient temperature and pressure, saturated with water vapor. ie uncorrected.)

TABLE 2 End-tidal carbon dioxide tension respiratory minute volume and respiratory rate.

RUNS AT 99 FEET												
WORK (20 minutes)							(REST (20 minutes)					
Main Period (15 min.)							Shift Period (5 min.)					
Main Period (15 min.)							Shift Period (5 min.)					
SUBJECT	pCO ₂	RMV*	Rate	pCO ₂	RMV*	Rate	pCO ₂	RMV*	Rate	pCO ₂	RMV*	Rate
	mm.Hg	L/min.	bpm	mm.Hg	L/min.	bpm	mm.Hg	L/min.	bpm	mm.Hg	L/min.	bpm
	No added D. S.			1000 added D.S.			No added D. S.			1000 cc added D.S.		
Coggeshall	36	37.4	14.4	34	29.0	21.5	25	10.4	10.4	29	7.0	8.5
Dwyer	48	42.0	15.6	57	32.5	16.5	38	10.6	4.0	38	12.0	5.5
Funderburk	58	29.0	9.8	58	27.0	14.0	47	10.2	4.0	43	9.0	4.0
Hanes	53	28.6	9.0	60	23.0	9.5	39	9.0	4.6	41	8.0	5.5
Hollingsw.	48	25.8	11.2	52	25.0	14.0	33	10.0	11.0	36	6.0	10.0
Lanphier	39	40.0	15.0	46	29.5	14.5	27	12.4	6.2	31	10.0	6.0
MEAN	47.0	33.8	12.5	51.1	27.7	15.0	34.8	10.4	6.7	36.3	8.7	6.6
	1000 cc added D.S.			No added D. S.			1000 cc added D. S.			No added D. S.		
Coggeshall	54	24.6	17.4	45	33.5	16.5	39	8.6	12.2	33	11.5	10.0
Dwyer	67	25.8	15.6	54	35.5	15.0	49	8.4	4.6	42	7.5	3.0
Funderburk	46	23.0	12.2	44	27.5	11.5	31	10.8	6.8	26	15.0	6.0
Hanes	53	16.6	10.2	47	22.5	10.5	32	4.6	6.0	31	5.0	4.0
Hollingsw.	(64)	(31.5)	(24.0)	--	--	--	39	10.6	10.4	36	9.5	9.0
Lanphier	33	41.0	22.0	31	46.0	20.0	26	13.0	10.0	23	15.0	7.0
MEAN **	50.6	26.2	15.5	44.2	33.0	14.7	36.0	9.3	8.3	31.8	10.6	6.5

*NOTE: RMV represents net volume of gas expired through meter. To obtain subject's total expired volume when breathing with dead space bag in circuit, add one liter per breath. (Values given are at ambient temperature and pressure, saturated with water vapor. i.e. uncorrected.)

**Means for work omit Hollingswoth (overworking - see Text 4.5.1).

TABLE 3.

MEAN p_{CO_2} VALUES AND DIFFERENCES $(p_{CO_2}$ Rounded to nearest mm Hg)

WORK - REST

SURFACENo D.S.
D.S.99 FEETNo D.S.
D.S.

MAIN PERIOD			SHIFT PERIOD			Mean difference
Work	Rest	Diff.	Work	Rest	Diff.	
45	37	8	46	36	10	9.0
48	38	10	47	38	9	9.5
47	35	12	44	32	12	12.0
51	36	15	51	36	15	15.0

SURFACE - DEPTH

WORKNo D. S.
D.S.RESTNo D.S.
D.S.

Surf.	99ft	Diff.	Surf.	99ft.	Diff.	
45	47	2	46	44	-2	
47	51	4	48	51	3	0 3.5
37	35	-2	36	32	-4	-3.0
38	36	-2	38	36	-2	-2.0

NO DEAD SPACE - DEAD SPACE

SURFACEWork
Rest99 FEETWork
Rest

No D.S.	D.S.	Diff.	No D.S.	D.S.	Diff.	
45	47	2	46	48	2	
37	38	1	36	38	2	2.0 1.5
47	51	4	44	51	7	5.5
35	36	1	32	36	4	2.5

TABLE 4.

RANK OF SUBJECTS ACCORDING TO END-TIDAL
(OR ARTERIAL) p_{CO_2} IN PREVIOUS STUDIES:
(in order of decreasing p_{CO_2} , mm Hg)

N ₂ O ₂ , 99 ft., WORK (1)			AIR, SURFACE, WORK (2)	
SUBJECT	p_{CO_2} (end-tidal)		SUBJECT	p_{CO_2} (art.) mean
	(3) mean	(3) max.		
DWYER	63	72	(6)	
CIRELLI (4)	62	67	CIRELLI	56.8
FUNDERBURK	61	68	HOLLINGSW.	50.7
HANES	61	62	COGGESHALL	47.0
HOLLINGSW. (5)	58	65	FUNDERBURK	44.4
COGGESHALL	56	56	HANES (7)	44.3
LANPHIER	40	44	LANPHIER	35.3
	(8)			

Notes:

1. Phase 2 data (See Formal Report 7-55)
2. Phase 3 data (See Formal Report 2-56)
3. Maximum values represent the highest recorded for the subject during any part of any run under these conditions. **Mean values** represent mean for last 5 minutes of work in one or more runs.
4. Note that CIRELLI was not a subject in the present series.
5. In one run in which he did not use "controlled breathing". mean p_{CO_2} was 51 mm Hg.
6. DWYER was not studied in Phase 3.
7. Appeared to be hyperventilating in run involving arterial puncture. Comparable run (end-tidal only) yielded p_{CO_2} of 47.9 mm Hg.
8. Average of mean values for subjects of present study is 56.6 mm Hg.

TABLE 5.

OXYGEN CONSUMPTION DATA
(Surface runs only, last 5 min-
minutes of main work-period.)

<u>SUBJECT</u>	<u>Dead Space</u>	<u>Oxygen Consumption liters per minute</u>
COGGESHALL	0	1.9
	+	1.2
DWYER	0	-
	+	1.8
FUNDERBURK	0	1.8
	+	-
HANES	0	1.6
	+	1.5
HOLLINGSWORTH	0	1.7
	+	1.4
LANPHIER	0	1.6
	+	1.5

TABLE 6.

BREATHING RESISTANCE

NOTE: Breathing resistance data was not analyzed in detail, but the following formula and "constants" permit calculating approximations and indicate the relative magnitude under various conditions.

$$P = (V)(k)$$

Where P = inspiratory or expiratory pressure (cm of water)

V = net RMV (liters)

k = constant

<u>CONDITION</u>	<u>CONSTANTS</u>	
	<u>WORK</u>	<u>REST</u>
<u>SURFACE</u>		
no d.s.	.17	.27
d.s.	.24	.37
<u>99 FEET</u>		
no d.s.	.34	.45
	.49	.55

8. APPENDICES

8.1 Acknowledgements

Sincere thanks are due to the subjects for their patience and cooperation, especially noteworthy because of the extreme discomfort involved in some of the runs. Credit is also due the hospital corpsmen and other EDU divers who assisted greatly as instrument operators and tenders. HMI FUNDERBURK should be mentioned especially for his work in building the dead space arrangements, rebuilding his end-tidal sampler for this study, and most of the setting-up of equipment.

A large contribution was made by the summer medical student trainee assistants, Martin Palmer, Andrew White, Alvin Szojchet, and Albert Loew, who devoted a large amount of time and hard work to adopting and using the two methods of measuring oxygen consumption, calibration of the bicycle ergometer, gas analysis, and the processing of data.

YN3 R.W. WILTERDINK deserves credit for the considerable job of typing this report.

8.2 Work rate (Refer to Procedure, 3.4)

During the course of the study, trouble developed with the bearings and pump-coupling of the bicycle ergometer. This added considerable friction and increased the work of pedaling. The difficulty was not readily corrected, and attempts to bring the work rate down to its proper level by reducing the pressure were not consistently successful. Since neither oxygen consumption nor carbon dioxide output were measured during depth runs, the work-rate became a fluctuating and unknown variable in many of the runs. This variability was accentuated by one subject who, it was later discovered, had chosen to ignore the rate-control indication. (See 4.5.1(3)).

8.3 Temperature (Refer to Procedure, 3.5).

Owing to the ineffectiveness of methods of controlling temperature during the 99-ft. runs, temperature and humidity were both obviously high. The subjects were acutely uncomfortable especially during work. They were drenched with perspiration which dripped from them and formed sizable puddles on the deck.

Although none of the more serious manifestations associated with heat-stress appeared, the subjects were unanimous in feeling that the heat made an otherwise tolerable procedure into an ordeal.

8.4 Arrangement of runs (Refer to Procedure, 8.4)

The 5-minute "shift" periods were included to obtain some indication of the effect of presence or absence of added dead space within each run, uncomplicated by the influence of day-to-day variations in the subject himself or in run-conditions. It was recognized that 5-minutes was not sufficient to permit reaching a steady state, but it seemed the longest practical period from the standpoint of subject-fatigue and decompression-time.

8.5 Preliminary dead space study (Refer to Discussion, 5.1.2)

A considerable study of dead space response under various conditions was conducted at EDU in the summer of 1954. Difficulties with carbon dioxide analyzer calibration were discovered which rendered several aspects of the results of questionable validity, and it was never formally reported. It can, however, be drawn upon for qualitative information concerning dead space response.

In a very small fraction of comparisons in this preliminary study, runs with dead space did show lower carbon dioxide levels than control runs without it; but under the circumstances of the study, these differences were readily attributable to day-to-day variations in carbon dioxide sensitivity. The only observations which really questioned the adequacy of current views were made in one subject (LANPHIER). When he breathed oxygen during work at the surface, he maintained the same p_{CO_2} despite addition of dead space volumes up to about 1.6 liters. **When breathing air** under the same conditions, showed only extremely small, smoothly progressive increases. (The runs concerned were all made at different times, each with a different increment of dead space; and the "oxygen" and "air" runs were interspersed in a random manner, so the consistency was impressive.) It was difficult to see how the usual stimulus-response concept could explain these findings, especially those with oxygen; but the question was never followed up. With understandable exceptions (See 5.2.3(3)), LANPHIER showed positive differences throughout the present study. In any case, nothing really resembling the questioned results of the present study has been described or observed to our knowledge.

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)		2a. REPORT SECURITY CLASSIFICATION	
Officer in Charge Navy Experimental Diving Unit Wash. Navy Yard, Washington, D.C. 20390		Unclassified	
3. REPORT TITLE		2b. GROUP	
NITROGEN-OXYGEN MIXTURE PHYSIOLOGY Phase 5 PROJECT NS185-005 SUBTASK 5 TEST 4			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)			
Final			
5. AUTHOR(S) (First name, middle initial, last name)			
LT Edward H. Lanphier, MC, USNR			
6. REPORT DATE		7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
20 February 1956		32	
8a. CONTRACT OR GRANT NO.		9a. ORIGINATOR'S REPORT NUMBER(S)	
b. PROJECT NO. NS185-005		RESEARCH REPORT 5-56	
c.		9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
d.			
10. DISTRIBUTION STATEMENT			
U.S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through Office of Technical Services, Department of Commerce, Washington, D.C.			
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY	
		Navy Experimental Diving Unit Washington Navy Yard Washington, D.C. 20390	
13. ABSTRACT			
<p>In Phase 2 of this project, it was noted that certain divers tended to develop high carbon dioxide levels during work while breathing nitrogen-oxygen mixtures at depth. This tendency is believed related to respiratory sensitivity to carbon dioxide. The latter might thus form the basis of practical personnel selection tests. The use of added respiratory dead space was considered a possible method of testing sensitivity, perhaps with the advantage of accentuating individual differences. The physiological effects of dead space in diving are also of concern in their own right. The present study was undertaken to assess the possible value of tests involving dead space under various conditions and to obtain more information about the physiological effects of dead space in diving.</p> <p>End-tidal carbon dioxide tension and other respiratory variables were measured in six subjects at the surface and at 99 feet in the dry recompression chamber during rest and work, with and without one liter of added respiratory dead space. Mean values showed an elevation of carbon dioxide tensions with addition of dead space, and large increases were noted in some subjects especially at depth. However, numerous individual comparisons indicated the reverse. Carbon dioxide levels were generally higher at depth than at the surface, but few approached the values recorded during nitrogen-oxygen exposure in Phase 2. Correlation with the subjects' relative levels of pCO_2 in Phase 2 was noted in (SEE NEXT PAGE)</p>			

13. ABSTRACT (continued)

certain phases of the study, but the relationships were not entirely entirely consistent.

Factors such as inability to control temperature at depth, certain characteristics of the dead space system, and instability of work rate were considered contributory to the variability and paradoxical nature of some of the results.

Further investigation is required before reaching firm conclusions, and several pitfalls revealed by this study must be avoided.